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USE OF SPACE TUG TO INCREASE PAYLOAD CAPABILITY OF SPACE SHUTTLE

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16. Abstract

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SUMMARY

An analysis has been performed to determine the increased payload capability of a space-shuttle—space-tug combination over that of the shuttle only. In this mode of operation, the space shuttle is assumed to transport the payload from the ground to a low orbit (185 km). At that point, the payload is transferred to a space-based tug which completes the trip to the space station (located in a 500-km orbit). An alternative mode considered was the use of an earth-based tug which is carried to and returned from orbit by the shuttle. It is shown that the payload capability of the shuttle can be increased by approximately 25 to 45 percent with the aid of either tug. The analysis also includes a study of the effect of variation in orbital inclination on payload capability for the two systems. The results indicated that the tug-shuttle combination is much more efficient in delivering large payloads to highly inclined orbits and can deliver payloads to much higher altitudes than the shuttle system alone.

INTRODUCTION

Economy will be the driving force in the development of a space-shuttle transportation system. In order to minimize the cost per kilogram of payload to orbit, the space shuttle must be a reusable and highly efficient system with its payload capability maximized for a given launch mass. The shuttle system as presently proposed (refs. 1 to 4) will be a fully reusable, two-stage vehicle in which all propellant tanks are retained and thermal protection is provided for reentry of both stages. As a result, the total inert mass of the second stage or orbiter element is large in comparison with the payload mass. Thus, a large amount of propellant is required for the orbiter element to transfer the payload from its low (185 km) phasing orbit to a 500-km space-station orbit. A more efficient system for performing this transfer would be an orbit-to-orbit shuttle or space tug. The same space tug can be utilized for other missions with the use of add-on modules for satellite insertion, retrieval, and repair. (See ref. 5.)

The purpose of this paper is to determine the maximum payload mass that can be delivered to the 500-km orbit by using a chemical, reusable space tug in conjunction with

the space shuttle. The payload masses of this study are compared with those obtained in recent contractual studies (refs. 1 to 4) that considered the space-shuttle concept only. The effects of orbital inclination and altitude on the payload capability of the two systems are also examined.

SYMBOLS

h_a	apogee altitude, km
h_p	perigee altitude, km
i	orbit inclination angle, deg
I_{sp}	specific impulse, sec
ΔV	on-orbit velocity increment, m/s

Abbreviations:

EBT	earth-based tug
SBT	space-based tug
ETR	Eastern Test Range

CONCEPTS

Reference Mission Concepts

The flight profiles of the space-shuttle and tug-shuttle reference mission concepts considered in this study are illustrated in figure 1. The space-shuttle reference mission with a typical two-stage, reusable vehicle is as follows. The first stage will launch the vehicle to a velocity of about 3 km/s and an altitude of approximately 61 km, where staging occurs. The first-stage element then either makes a 180° turn and flies back to base or lands at a downrange site, while the second-stage shuttle is injected into elliptical orbit $\left(h_p = 83\ \text{km} \text{ and } h_a = 185\ \text{km}\right)$. The orbit is then circularized at 185 km for phasing purposes. After phasing, the mode followed in previous studies (refs. 1 to 4) is for the shuttle with its payload to transfer from the 185-km to a 500-km, 55° inclined orbit. There the shuttle will rendezvous with a space station and payloads will be interchanged. With its return payload, the shuttle then deorbits, enters the atmosphere, and maneuvers so that it can land at a desired site.

For the tug-shuttle reference mission concept considered in the present study, it is assumed that a reusable, chemically propelled tug would operate from a 500-km baseline orbit. Such a tug would be used to transport return payload from this orbit down to the 185-km orbit, where it would circularize its orbit and rendezvous with the space shuttle. Payloads of the two vehicles would then be interchanged and the tug would carry the shuttle's ascent payload to the 500-km orbit, while the shuttle would descend to earth with the return payload. For the interorbital transfer, the tug, due to its low inert mass, is a considerably more efficient system than the shuttle as will be demonstrated in the section entitled "Mass Analysis." An artist's illustration of this concept is presented in figure 2. Shown at the far left of this figure is the rendezvous phase of the tug and shuttle in the 185-km orbit. The tug system is assumed to be composed of propulsion, crew, and payload modules. Also depicted is the shuttle with its payload being transferred from the cargo bay. The center sketch shows the tug docked to the ascent payload having delivered the descent payload. At the right the tug ascends to the space station with its payload and the shuttle transfers the descent payload into the cargo bay before returning to Earth.

Upon arrival at the space station, the space tug can dock and transfer its payload with considerably greater ease than could the shuttle. The shuttle's large mass, which is of the same order as the space station mass, makes it quite difficult to achieve a "soft" contact between the two systems. Thus, a space tug would probably be needed for payload transfer at the space station in any case.

Alternative Mission Concepts

Two alternative missions are considered here since the shuttle-tug system as currently envisioned will supplant most of the existing launch vehicles. One alternative mission which was considered is the delivery of payloads to orbit inclinations other than the reference 55° orbit. The second alternative mission considered is the delivery of the payloads to higher orbital altitudes.

MASS ANALYSIS

The efficiency of operation of a space tug is, of course, strongly dependent on the amount of inert mass which must be carried along. The mass of representative subsystems (as determined in ref. 5) is presented in table 1 for a manned space tug using an RL-10 class of engine system. The total mass of this manned tug system, excluding propellant and tanks, was estimated to be about 1815 kg.

If an unmanned tug system with a docking module were used, the system mass, excluding propellant and tanks, would be only about 550 kg, according to reference 5.

With this system, the efficiency in transporting payload could be increased above that of the manned system provided unmanned remote operations could be achieved. However, it is the purpose of this paper to demonstrate the desirability of the present concept. Therefore, the conservative approach of the use of the heavier manned space tug is assumed hereafter.

In order to determine the propellant and tank masses for the manned space tug, velocity requirements must be defined. Presented in table 2 are the on-orbit impulsive velocity requirements for payload transfer from the injection orbit to the space-station orbit. Velocity requirements are given for both the previously studied shuttle only concept (obtained from refs. 1 to 4) and the present tug-shuttle combinations. Circularization of the shuttle at an altitude of 185 km requires a velocity increment of approximately 30 m/s when transferring from an initial elliptical orbit $\left(h_p = 83 \text{ km} \text{ and } h_a = 185 \text{ km}\right)$. In order to transfer the shuttle from the 185-km to the 500-km orbit, including rendezvous and docking maneuvers, a ΔV of about 213 m/s is required. For launch dispersions and plane change, a ΔV of 61 m/s is allocated and deorbit requires a ΔV of about 153 m/s. Finally, a ΔV of 153 m/s is allocated for contingencies. Thus, a total on-orbit ΔV requirement for the shuttle only mode of 610 m/s is needed. The tug-shuttle combination requires a shuttle ΔV capability of 30 m/s for circularization at 185 km, 153 m/s for deorbit, and 46 m/s for contingencies. The tug requires a ΔV capability of 213 m/s for descent and rendezvous, 213 m/s for ascent and rendezvous, 61 m/s for launch dispersion and plane change, and 76 m/s for contingencies. Thus, the combined tug-shuttle system requires a total ΔV of 792 m/s. Most of the analysis in this study will be based on these values. The effect of reduced total velocity will, however, be examined since the values allotted to contingencies, launch dispersion, and plane change can possibly be decreased considerably.

An example of the amount of propellant required to obtain the on-orbit maneuvers with a typical shuttle and a tug-shuttle combination is illustrated in table 3. The shuttle is representative of a 11 350-kg baseline payload system as considered in references 1 to 4 for missions to a 55° inclined 500-km orbit. The propulsion system for both the tug and the shuttle is assumed to have a specific impulse of 450 seconds. Propellant requirements for the on-orbit maneuvers for the baseline shuttle are about 12 300 kg, which is large because the shuttle must accelerate a total mass of approximately 95 000 kg. When the shuttle is used in conjunction with a tug, the propellant required for the shuttle is 650 kg for circularization and 4050 kg to deorbit at the 185-km altitude. The remaining 7600 kg at this point may then be considered as additional payload above the 11 350-kg baseline shuttle payload, if it is assumed that the tug draws its propellant from a propellant storage facility located near the space station. Enough propellant to support several subsequent missions could be carried up from Earth during one flight and stored in the space propellant storage facility. But to make a fair comparison with the shuttle, it is

assumed that the propellant required for the tug is charged against the ascent payload. In this case (see table 3), the transfer of the tug with its payload from the 500-km to the 185-km orbit and back to the 500-km orbit requires only about 2500 kg of propellant because the total mass to be transferred is relatively small (approximately 21 000 kg). This total mass includes the basic tug, payload, propellant, and tanks which were assumed to be 10 percent of the propellant mass. Thus, the tug-shuttle combination requires only 7200 kg of propellant which leaves 5100 kg left for additional payload. Thus, a nominal payload capability of 16 450 kg is provided by the tug-shuttle as compared with 11 350 kg for the shuttle. Consequently, for a fixed cargo volume of the shuttle, the payload density must be increased with use of the tug concept for maximum payload to orbit.

INCREASED PAYLOAD

Using the preceding approach, the increased payload capability afforded by the space tug is presented in figure 3 as a function of the mass of various space-shuttle systems in an initial elliptical orbit $\left(h_p = 83 \text{ km} \text{ and } h_a = 185 \text{ km}\right)$ for both 11 350- and 22 700-kg payload class of shuttles. The symbols are based on contractual studies (refs. 1 to 4) from which some of the mass required for propellant for the shuttle only concept has been translated into additional payload mass with use of the tug system. Considering first the 11 350-kg payload class of shuttle (fig. 3(a)), the payload mass deliverable to a 55° inclined, 500-km orbit can be increased from 3500 to 6500 kg (depending on the shuttle mass in the initial orbit) or an average of about 45 percent above the baseline of 11 350 kg if a space-based tug (SBT) is employed. A reduction in payload gains of about 1800 kg is associated with use of an earth-based tug (EBT). This tug is carried from Earth to orbit and returned by the shuttle on each mission. The flagged symbols in this figure represent shuttle configurations having a cargo bay with a diameter of 4.6 m and a length of 9.15 m, and the unflagged symbols represent a 4.6- by 18.3-m cargo bay. However, there appears to be no distinct correlation of mass with the cargo size.

For the 22 700-kg baseline payload case (fig. 3(b)), the additional payload mass capability of the tug-shuttle ranges from about 3100 to 7000 kg for the EBT and from about 5000 to 8500 kg for the SBT, or an average of about 25 percent above the shuttle payload, depending on the tug mode used. This percentage is not as large as that for the 11 350-kg baseline case, because the initial shuttle mass in orbit is not a linear function of payload mass.

The tug-shuttle payload gain can be used to reduce the number of flights required to deliver a desired amount of mass to the space-station orbit. (See fig. 4.) For illustration purposes assume that the space shuttle can be used to transport 450 000 kg of the total Mars vehicle mass to Earth orbit for a manned Mars mission. Delivery of this amount of mass to a 500-km orbit requires 40 flights with a 11 350-kg baseline payload

shuttle and 20 flights for the 22 700-kg shuttle. This number of flights can be reduced by about 25 to 30 percent with use of a tug-shuttle combination.

LAUNCH MASS REDUCTION

The efficiency of the tug can also be used to reduce the space-shuttle lift-off mass for a given payload to a space-station orbit (500 km). (See fig. 5.) The solid and dashed lines represent average values of the point design shuttle studies (refs. 1 to 4) and comparable tug-shuttle results, respectively. It can be seen that for a given or desired payload mass the total launch mass requirement can be reduced by about 260 000 kg with the aid of the SBT system. On the other hand, for a given launch mass, the SBT-shuttle provides substantially larger payload capability than the shuttle as discussed previously.

ON-ORBIT ΔV EFFECTS

The payload capability of both the shuttle and the tug-shuttle combination is strongly affected by the total on-orbit velocity requirement. An illustration of this effect is given in figure 6. The baseline points shown here are for an on-orbit ΔV of 610 m/s for the shuttle and 792 m/s for the SBT-shuttle. Since the contingencies and plane change velocities given in table 2 seem to be very conservative based on the current shuttle studies, it has been estimated that the total on-orbit velocity may be reduced to about 450 m/s. The payload of the shuttle would then be increased from 11 350 to 14 000 kg. With a comparable reduction in on-orbit velocity for the tug, the tug-shuttle system would still provide about 3000 kg of greater payload capability than the shuttle. As may be noted from the slopes of the curves, reduction of on-orbit ΔV is more beneficial to the shuttle.

ORBIT INCLINATION EFFECTS

Up to this point only a 55° inclined, 500-km orbit has been analyzed. Other orbit inclinations will be required for missions ranging from Earth resources to planetary probe injection. Obviously, the payload delivery capability of any launch system is a function of the desired orbital inclination and altitude and of the launch site latitude. For the present study, the desired orbital inclination is achieved by launching from Earth at the proper azimuth angle, because changing the inclination after reaching orbit would require an extremely large velocity increment. The shuttle is, therefore, used to place the payload as well as the space tug into an initial 185-km orbit with the desired inclination angle. Transfer of the payload from this point to a higher altitude is performed by either the shuttle or the space tug as described previously.

The effect of orbital inclination on the payload deliverable to a 500-km orbit is presented in figure 7. For these results, the Eastern Test Range (ETR) launch site is assumed. As the orbital inclination angle is increased, the payload capability of all shuttle modes is reduced significantly. The payload for the EBT-shuttle, however, is approximately 3200 kg above that of the shuttle at all inclinations. On a payload percentage basis the EBT-shuttle is more effective at the higher inclinations. As an example, for a polar orbit (90°) the EBT-shuttle payload is above 50 percent greater than that of the shuttle. The payload can be increased further if a SBT is located in the desired inclined orbit.

ORBITAL ALTITUDE EFFECTS

For some future satellite missions, it will be desirable to place a given payload mass at a very high altitude. Shown in figure 8 is the effect of orbit inclination on the maximum orbital altitude attainable with a 11 360-kg payload launched from the Eastern Test Range. Both insertion and insertion-retrieval of payload were considered. In all cases the shuttle and the EBT-shuttle are returned to Earth. As expected, increasing the orbit inclination decreases considerably the orbital altitude attainable by the shuttle and the EBT-shuttle. However, the tug-shuttle can attain much higher altitudes than the shuttle. For orbit inclinations up to 70°, final altitudes greater than 1000 km are achievable with the tug-shuttle carrying a 11 350-kg payload. Obviously, maximum altitudes are obtained for the payload insertion missions.

CONCLUDING REMARKS

This study has shown that a space tug can be used to increase substantially the payload capability of a given space-shuttle system. Typical payload gains from 25 to 45 percent above baseline shuttle values for missions to a 55° inclined, 500-km space station orbit can be realized with the tug. On the other hand, for a given payload, the total launch mass requirement of the shuttle for a space-station mission can be reduced significantly with the aid of the tug. The tug-shuttle combination is also much more efficient in delivering larger payloads to highly inclined orbits and can deliver payloads to much higher altitude orbits than the shuttle system alone.

On the basis of this analysis, the tug-shuttle concept warrants more detailed study at the systems and operational levels.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 27, 1971.

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TABLE 1.- MASS ESTIMATES OF BASIC MANNED SPACE TUG*

Subsystem	Mass, kg
Propulsion	105
Module structure	476
Environmental control	227
Two-man crew and provisions	227
Electronics and other systems	780
Total system (excluding propellant and tanks)	1815

*From reference 5.

TABLE 2.- ON-ORBIT IMPULSIVE VELOCITY REQUIREMENTS

Maneuver	Shuttle ΔV, m/s	Combination	
		Shuttle ΔV, m/s	Tug ΔV, m/s
Circularize at 185-km altitude	30	30	
Transfer from 185-km to 500-km orbit (including rendezvous and docking)	213		213
Launch dispersion and plane change	61		61
Deorbit from 500 km for entry	153		
Transfer from 500-km to 185-km orbit			213
Deorbit from 185 km for entry		153	
Contingencies	153	46	76
Subtotal		229	563
Total	610	792	

TABLE 3.- TYPICAL MASS BREAKDOWN USING SPACE TUG

[Shuttle baseline payload = 11 350 kg; I_{sp} = 450 sec]

Function	Propellant mass, kg	Approximate accelerated mass, kg	ΔV, m/s
Baseline shuttle on-orbit maneuvers	12 300	95 000	610
Circularize shuttle at 185-km altitude	650	95 000	30
Deorbit shuttle at 185-km altitude	4 050	92 500	199
Tug transfer from 500-km to 185-km to 500-km orbit	2 500	21 000	563
Additional payload mass provided by space-based tug	5 100		

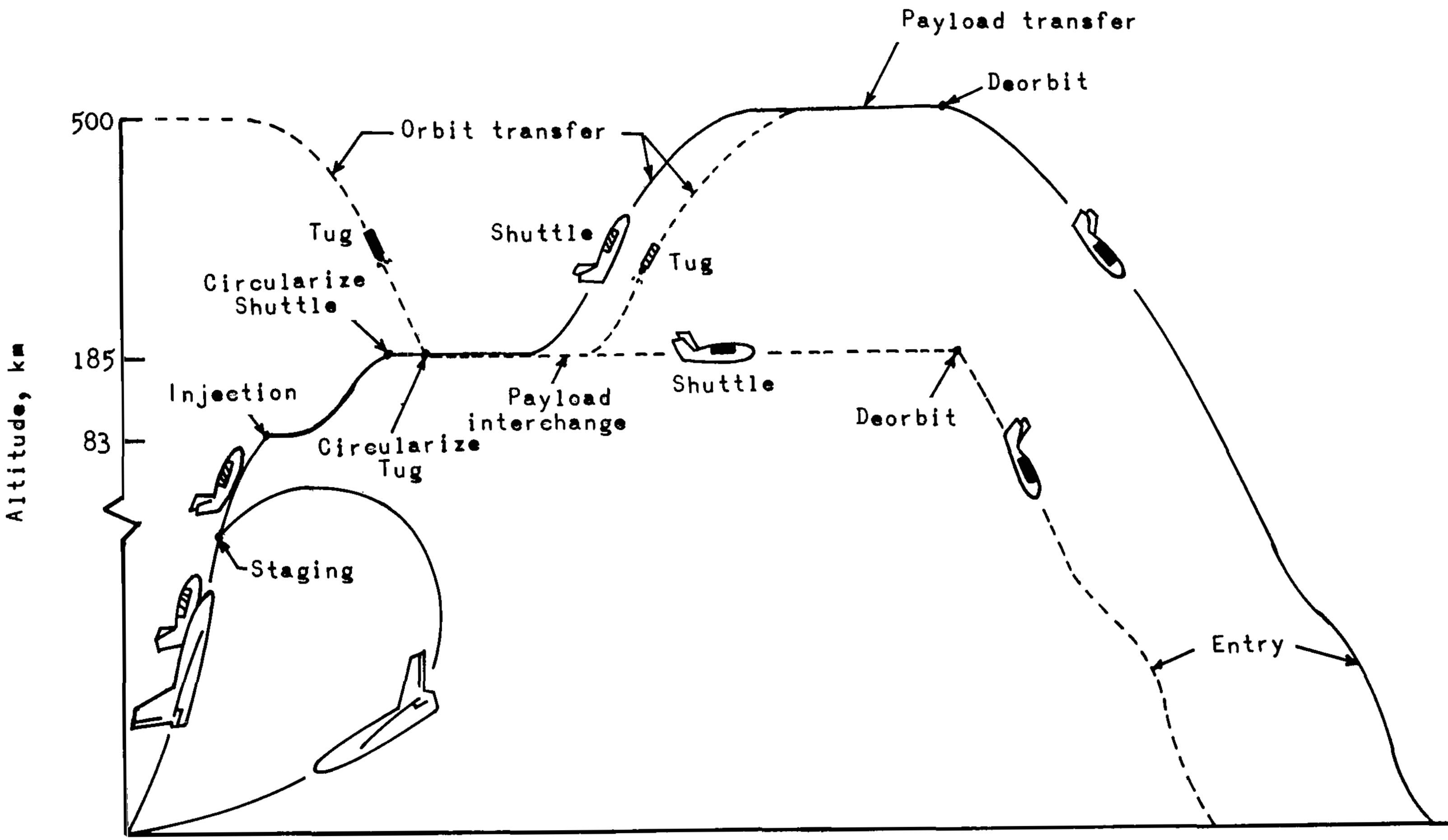


Figure 1.- Space-shuttle and space-tug flight profiles.

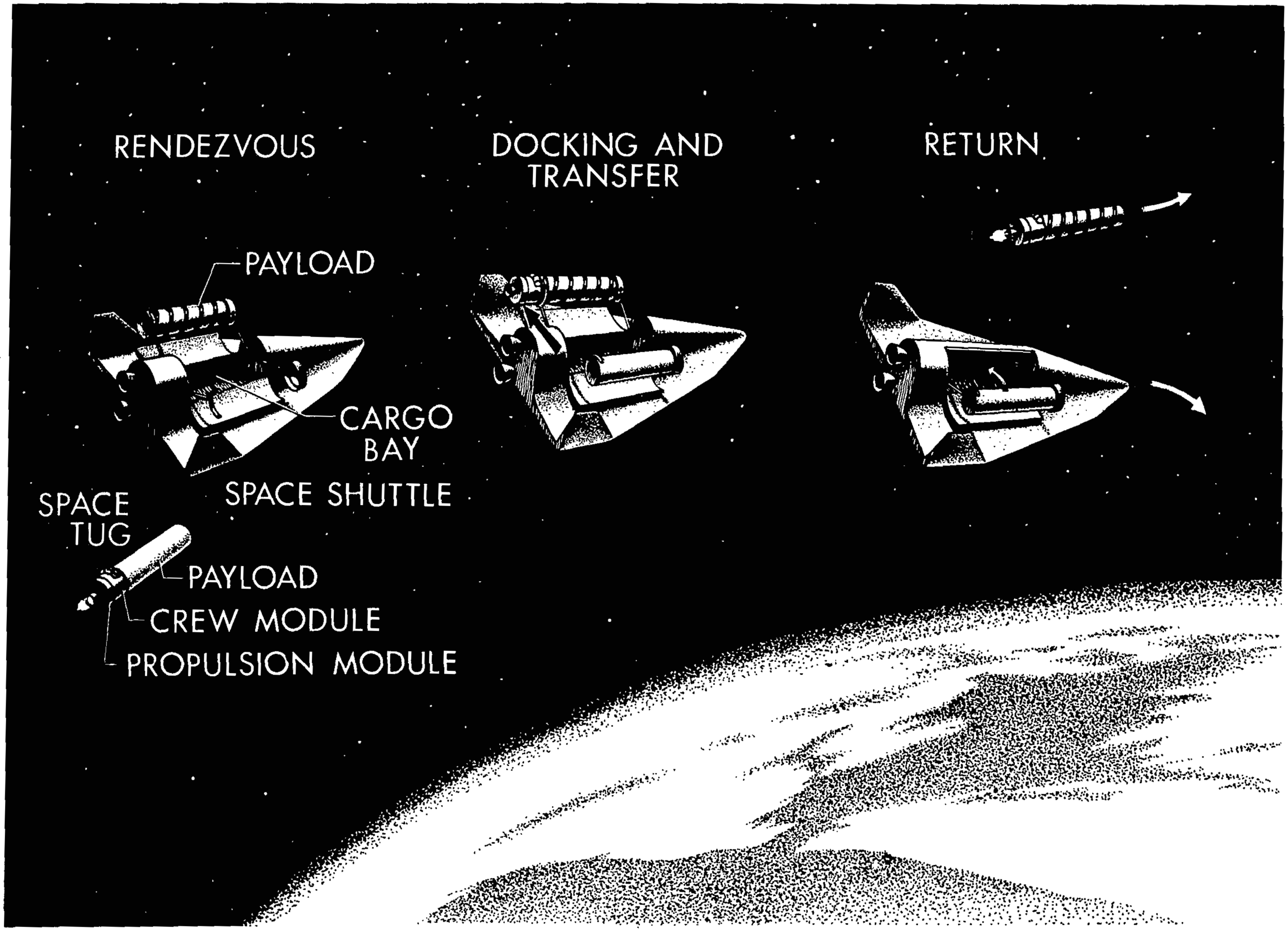
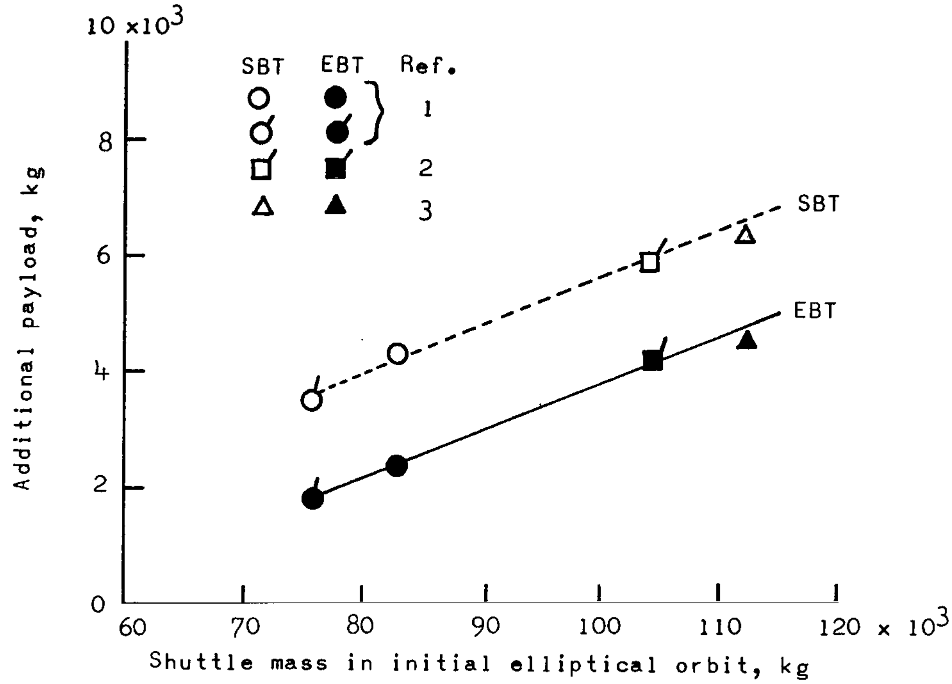
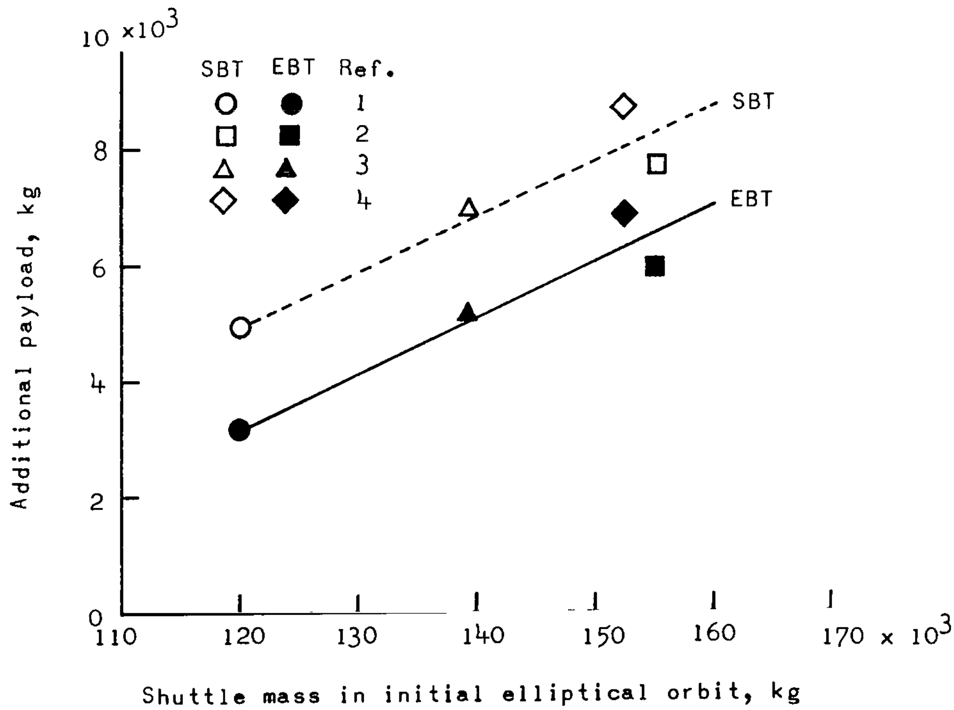


Figure 2.- Transfer of payloads between the space tug and space shuttle.



(a) Shuttle baseline payload of 11 350 kg.



(b) Shuttle baseline payload of 22 700 kg.

Figure 3.- Increased payload capability to 500-km circular orbit by use of space tugs in combination with various shuttle systems. $i = 55^\circ$; shuttle initial elliptical orbit $\left(h_p = 83 \text{ km} \text{ and } h_a = 185 \text{ km}\right)$.

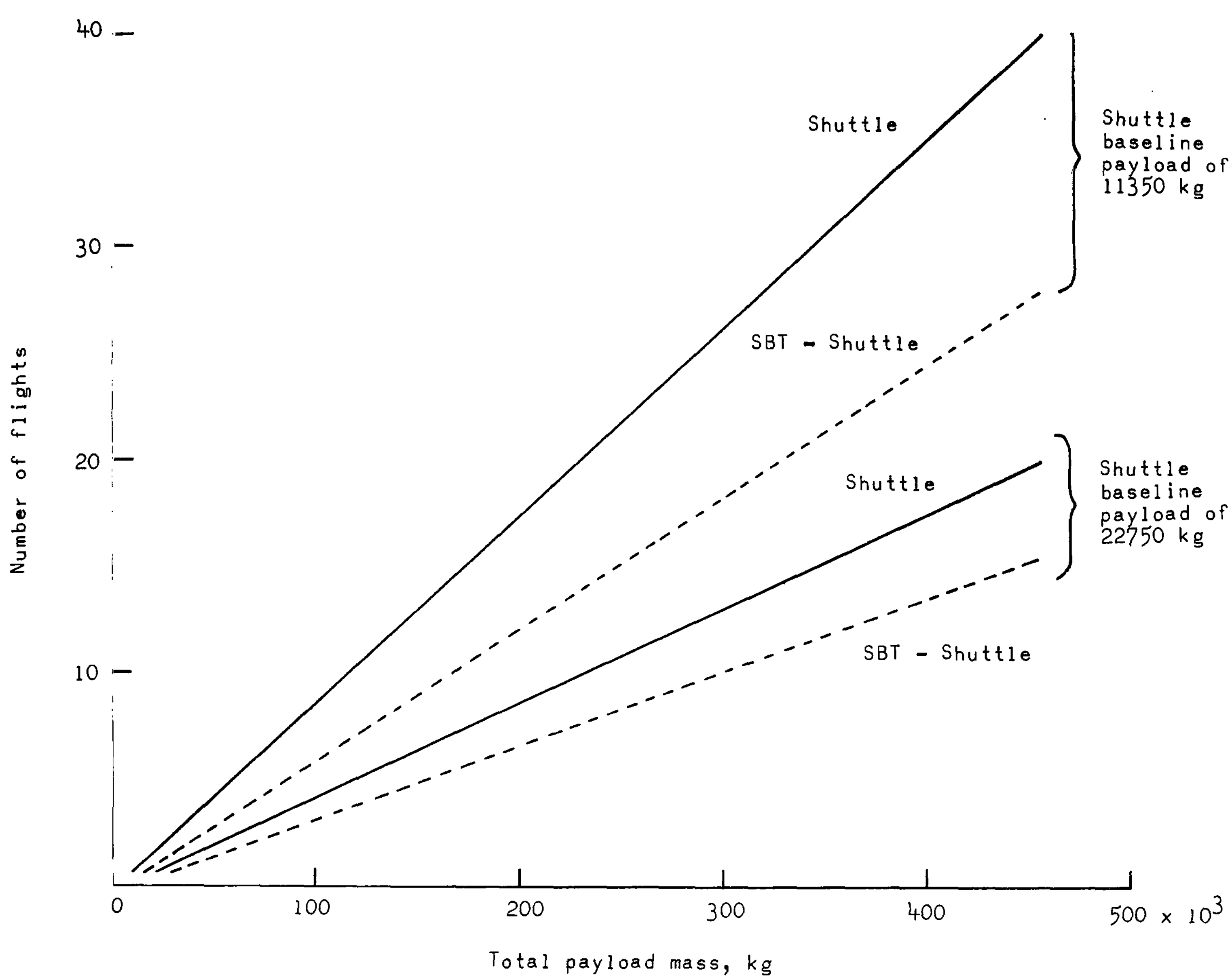


Figure 4.- Number of flights required to deliver various payloads to a 500-km circular orbit. $i = 55^{\circ}$.

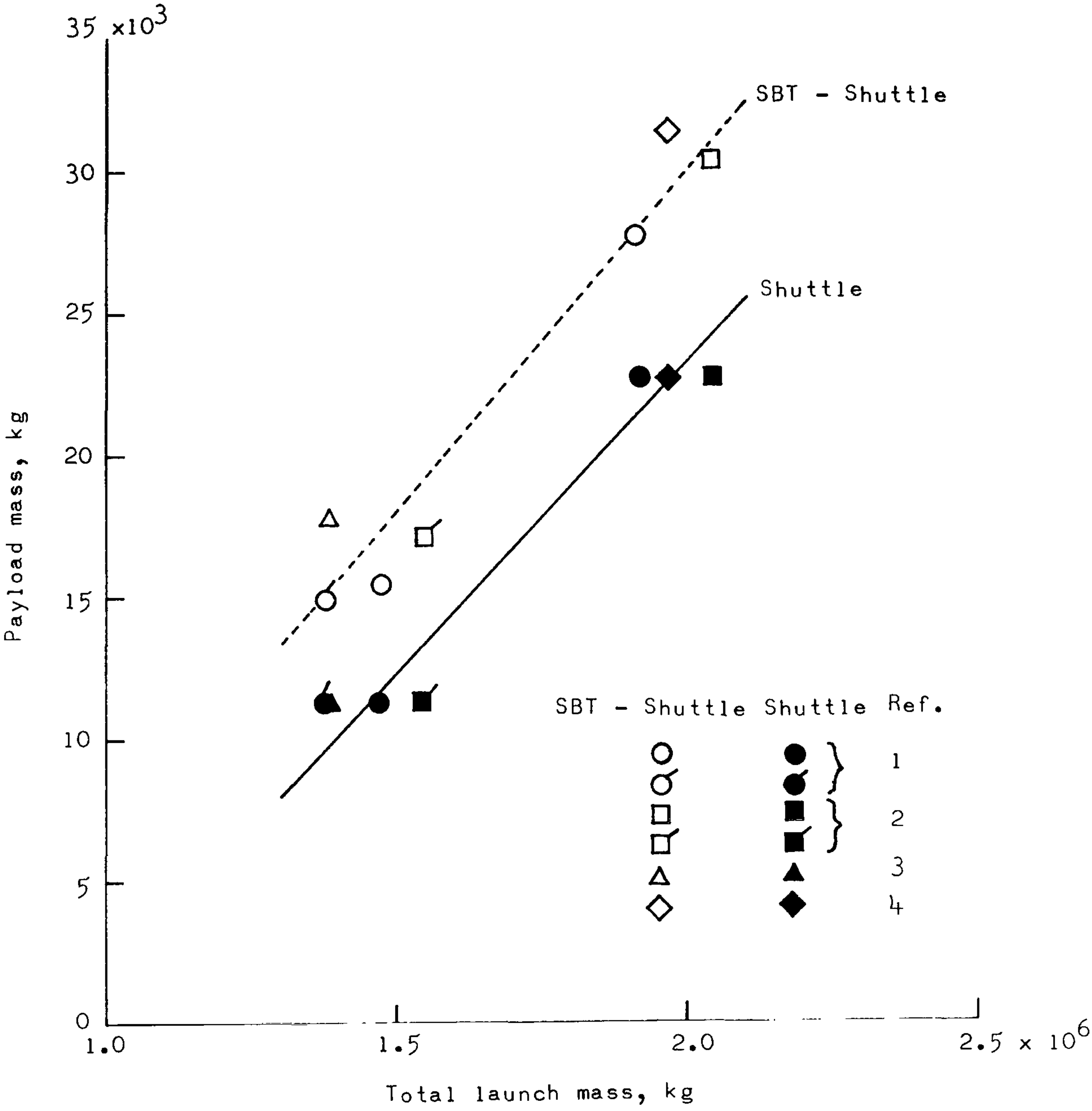


Figure 5.- Payload capability as a function of launch mass. 500-km circular orbit; $i = 55^{\circ}$.

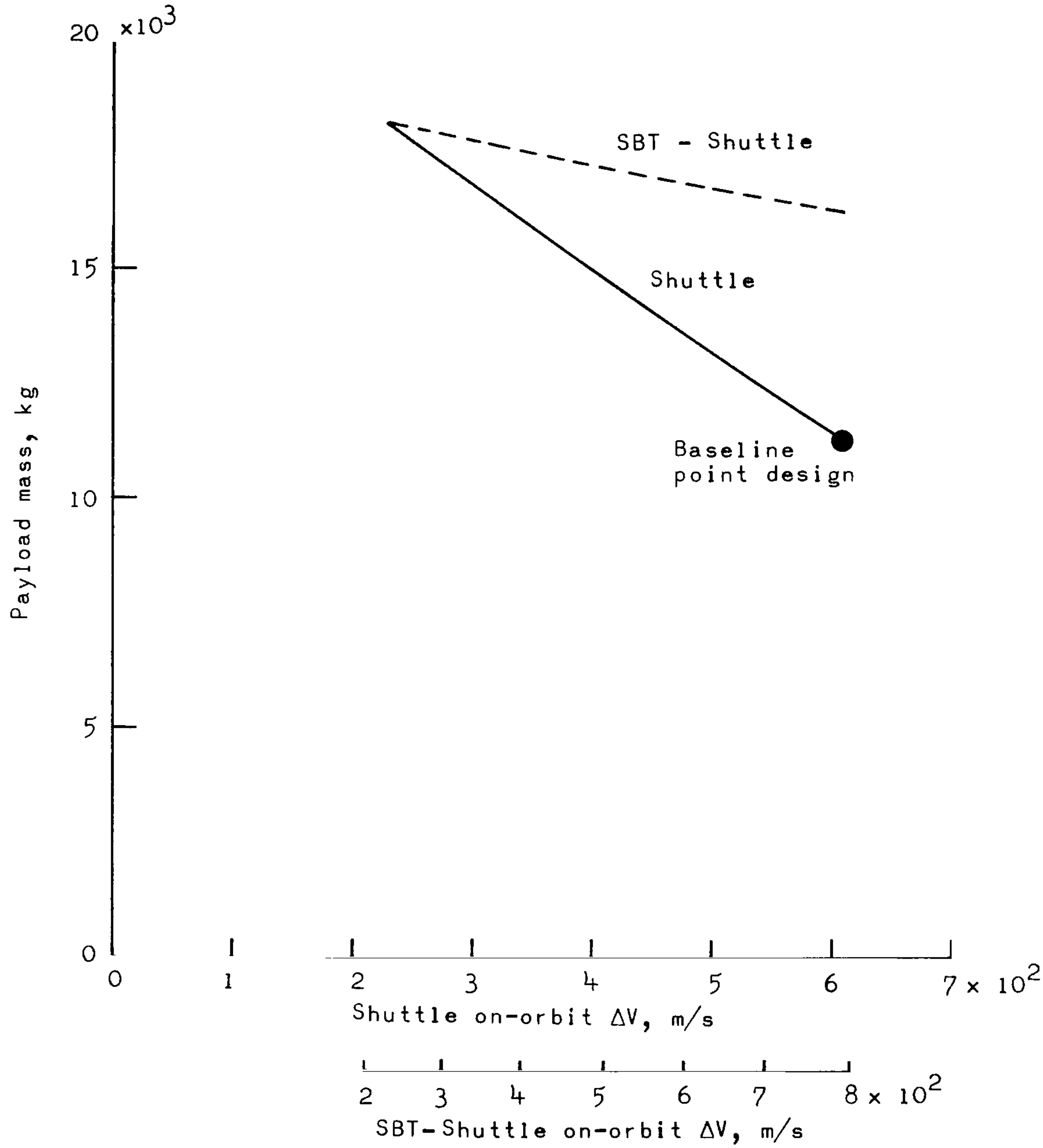


Figure 6.- Variation of payload mass with on-orbit ΔV requirements.

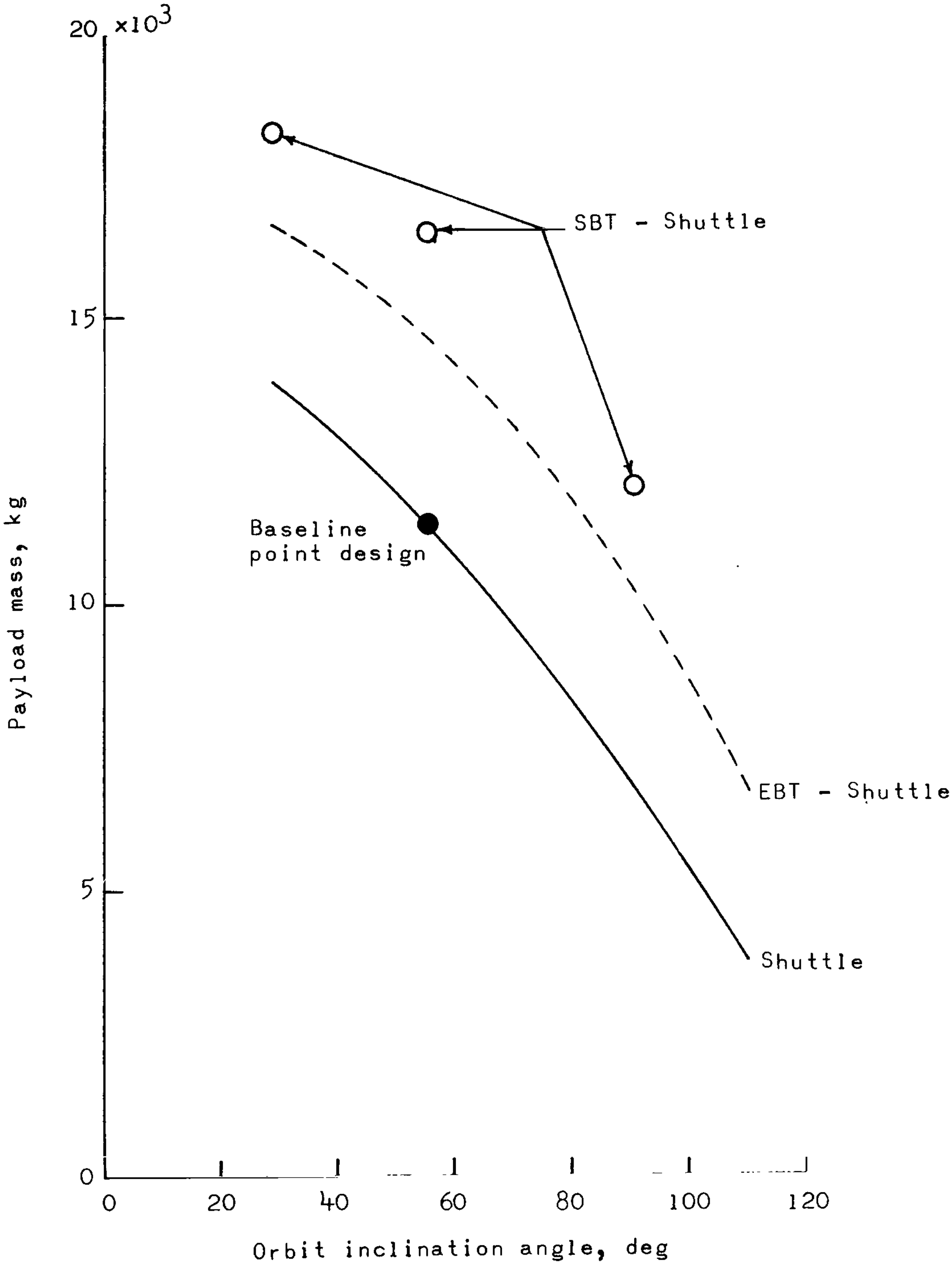


Figure 7.- Effect of orbit inclination on payload. 500-km circular orbit; launch from ETR.

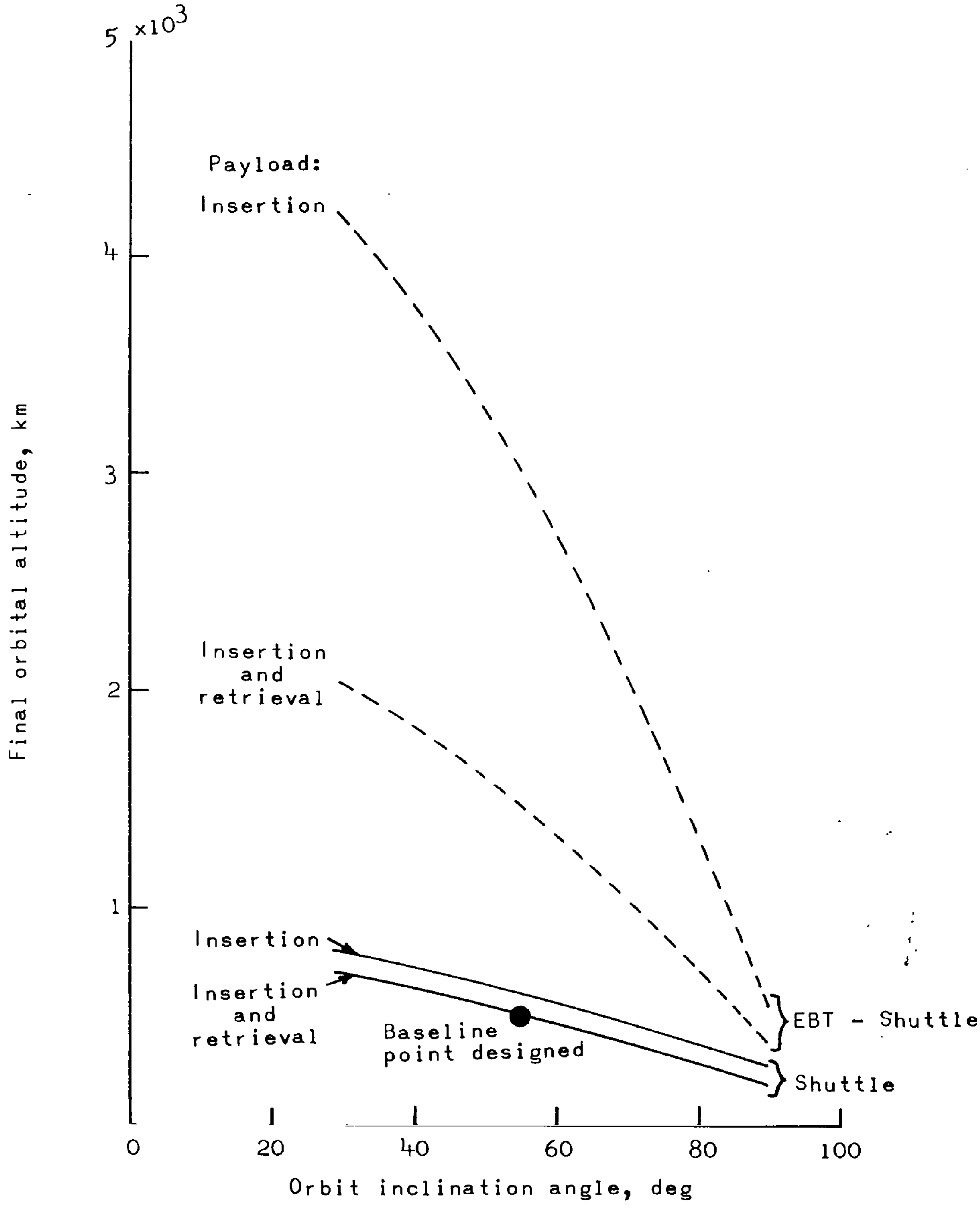


Figure 8.- Maximum orbital altitude attainable. 11 360-kg payload; launch from ETR.

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